1

Giant Outflows in powerful z∼2 Galaxies: The Smoking Gun of AGN Feedback in the Early Universe

1.1 Introduction

AGN feedback is now a critical component of models of galaxy formation, introduced to bring several outstanding issues of our hierarchical picture of galaxy evolution into agreement with observations [1, 2]. The energy ejected by powerful AGN is similar to the binding energy of the massive host galaxy and may therefore *in principle* be sufficient to offset cooling and star formation in galaxies [3, 4]. However, it is not clear by what mechanism this energy is being transformed into kinetic energy of the gas.

Observationally a picture emerges where this energy transfer may occurc mostly through the relativistic, synchrotron-emitting plasma ejected by radio-loud AGN [5, 6, 7]. However, most of these observations focus on galaxies at low redshifts, whereas the main formation phase of massive galaxies was in the early Universe, at redshifts z ∼2. Largely driven by the evolution of the host galaxy and its surroundings, the role of AGN in regulating star formation may be different in galaxies at high redshift compared to galaxies today. At high redshift, the energy injected into the interstellar medium may have contributed to "quenching" the vigorous starbursts during the main formation phase of a massive galaxy, by heating and removing the molecular reservoirs of star formation ("quenching phase"). At low redshift, subsequent, perhaps repeated and weaker phases of AGN activity may play a role in inhibiting further gas cooling over significant cosmic times ("maintenance phase").

1.2 Giant outflows in powerful radio galaxies at z∼2

Powerful radio galaxies are ideal targets to search for the fingerprints of AGN feedback in the early Universe. They are particularly massive [8, 9] and as a population are likely undergoing a transition from strongly star forming

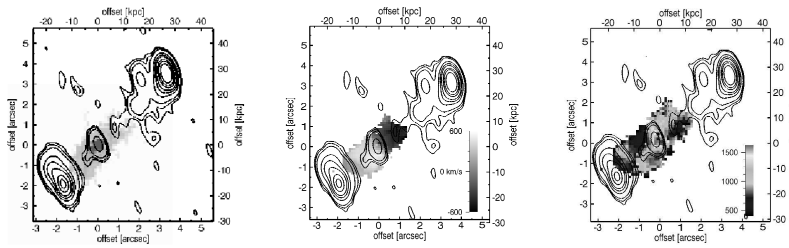

Fig. 1.1. *left to right:* Emission-line morphology, and maps of relative velocities and line widths (Full widths at half maximum) of MRC0406-244 at z=2.4. For a color version of this figure see [19].

to 'old, red, and dead' [10, 11]. They are also the hosts of particularly powerful, radio-loud AGN. Deep Lyα spectroscopy, including integral-field spectroscopy, shows that many radio galaxies are embedded into Mpc-sized gaseous reservoirs, perhaps the 'vestiges' from which the radio galaxy initially formed [13, 12, 15, 38, **?**].

Using rest-frame optical integral-field spectroscopy at the VLT, we identified spatially extended, kpc-sized outflows of ionized gas which correspond to significant fractions of the interstellar medium of a massive, gas-rich galaxy [17, 18, 19], and which have about solar metallicity [20]. Based on the observed Hα emission-line luminosities, electron densities measured from the [SII]$\lambda\lambda$6716,6731 line ratio, and simple case B recombination, we estimate gas masses of ionized gas of everal 10^{10} $M_{\odot}$. This corresponds to the molecular gas masses in the strongest starburst galaxies at similar redshifts. This is also similar, or even exceeds, the molecular gas masses in those galaxies of our sample for which we have direct estimates of the cold molecular gas mass measured from the CO line emission. This may suggest that the outflows indeed include a significant fraction of the interstellar medium of these galaxies.

Using imaging spectroscopy, we also infer the kinematics and kinetic energy of the gas. We find relatively uniform velocity patterns with one strongly redshifted and one strongly blueshifted bubble suggestive of a biploar flow (Fig. 1). Measured velocity offsets are of order 1000 km s^{-1} between bubbles, not correcting for inclination. Line widths of FWHM∼800-1000 km s^{-1} suggest this gas is very turbulent.

Several arguments indicate that a 'cocoon' of hot, overpressurized gas inflated by the radio jet may be the main driver of accelerating and ionizing the dense and warm gas we observe in the optical line emission. (1) Geometry: The major axes of the emission-line regions are aligned with the

axes of the radio jet and extend significantly beyond the size of the stellar continuum. Although being elongated along the jet axis, the morphology of the gas suggests a significant lateral expansion, and not just a very localized interaction along the jet working surface. The spatial extent of the emission-line regions is smaller than the size of the radio lobes. Galaxies with compact radio sources have compact line emission. (2) Timescales: From the observed gas velocities and size of the emission-line regions we can roughly estimate outflow times of few $\times 10^7$ yrs, similar to typical AGN lifetimes, and significantly less than the typical duration of a starburst. (3) Energy: Observed kinetic energies are sufficient to unbind up to $\sim 10^{11}$ $M_\odot$ of gas from a massive host galaxy [17]. Comparing the energy injection rate of the AGN with the energy needed to drive the observed gas kinematics, we find that about 10% of the jet kinetic power are needed to explain the gas motion. Using this efficiency and relating the rest-frame energy equivalent of the supermassive black hole with the kinetic energy of the outflows, we find that about 0.1%−0.2% of the energy equivalent of the black hole is used to power the outflows [19]. This is in good agreement with what is assumed in models of galaxy evolution.

As discussed in [17, 19] it appears that these outflows may terminate star formation in a way that is consistent with requirements from chemical evolution models. Subsequent accretion of satellite galaxies observed around some z∼2 radio galaxies is likely not sufficient to significantly alter these properties [19, 21].

Extended line emission with blueshifted and redshifted gas at high redshift is often regarded as evidence for rotation, even in cases where the low spatial resolution of the data make it very difficult to robustly differentiate between abrupt velocity changes smeared out by the seeing and intrinsically smooth velocity gradients indicative of rotation [22, 23, 24, 25, 26, 27, 28, 29]. Due to the large spatial extend of the line emission in radio galaxies this constraint is somewhat alleviated. Nonetheless it is interesting to point out that the measured velocity offsets and sizes of the emission-line regions would correspond to virial masses of up to 10^{15} $M_\odot$ within a radius of ∼20 kpc, not correcting for extinction. This is similar, or even exceeds, mass estimates for the dark-matter halos underlying the overdensities of galaxies observed around some radio galaxies (which may represent collapsing protoclusters [30, 31, 32]) out to Mpc scales. Thus the observed emission-line kinematics are clearly supergravitational. Starbursts at high redshift do not produce much higher emission-line surface brightnesses than strongly star-forming regions at low redshift and are thus not sufficient to explain the immense

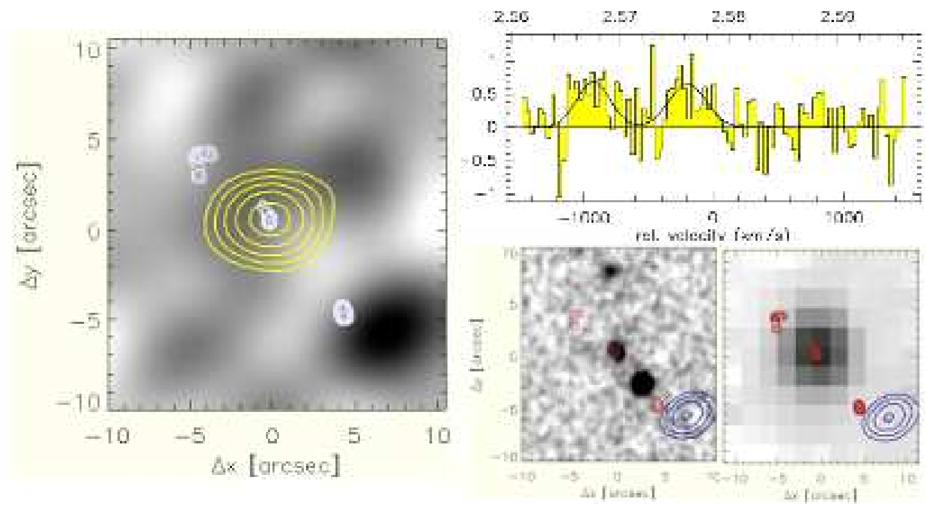

Fig. 1.2. *left:* CO(3-2) line image of TXS0828+193 at z=2.6. We only detect the 3mm continuum at the position of the radio source (thick contours). Luminous CO(3-2) line emission originates from a region 90 kpc SW from the radio galaxy, and near one of the radio hot spots (thin contour). The source is not spatially resolved at our 5 arcsec beam ($\sim$ 40 kpc). *top right:* The spectrum shows two components at redshifts which are in excellent agreement with that of the diffuse Lyα emission found at similar radii from the radio source. *bottom right:* We do not detect a counterpart at rest-frame UV to infrared wavelengths. The left panel shows an overlay with deep K-band imaging, the right panel shows our MIPS 24μm image. Contours mark the position of the cm radio source and the CO line emitter, respectively. For color versions of these figures see [35].

Hα luminosities of our targets [33] or the observed mass loss rates in ionized gas [34].

Comparison with cooling-flow clusters at low redshift does not suggest that the bright, turbulent emission-line regions we observe in the rest-frame optical are related to massive cooling flows: In low redshift clusters, the emission-line gas seems to avoid the radio lobes, whereas at high redshift, emission-line regions and radio emission are well aligned. Moreover, we find that the blueshifted bubble is always on the side of the radio lobe with higher polarization. If the Laing-Garrington effect approximately holds, this suggests that the blueshifted gas is along the approaching radio lobe indicative of a net outflow from the host galaxy [19].

1.3 Evidence for AGN heating of the intracluster medium in the early universe?

Our millimeter observations of CO line emission in z$\sim$2 radio galaxies may also have yielded the first observational signature of the deposition of parts of the mechanical energy of the radio jet into the intracluster medium at high redshift [35]. To explain the high entropy floors of X-ray luminous, massive galaxy clusters at low and intermediate redshifts, models of galaxy evolution now postulate a phase of efficient 'pre-heating' through the AGN at high redshift, during the collapse of the cluster [36, 37].

Using the IRAM Plateau de Bure Interferometer we detected faint CO(3-2) line emission in the halo of the powerful radio galaxy TXS0828+193 at z$\sim$2.6 which is at a distance of $\sim$90 kpc from the radio galaxy, and does not seem associated with a significant stellar mass greater than several $\times 10^9$ $M_\odot$ [35]. This is in stark contrast to all other galaxies at similar redshifts detected in CO. We also do not detect the source in 24μm MIPS imaging, which covers the PAH bands in the rest-frame mid-infrared, suggesting this gas is not forming stars at the prodigious rates typically observed in massive, gas-rich high-redshift galaxies.

This gas is near the hotspot of one of the radio jets of TXS0828+193, and we detect two components with velocities that seem to 'straddle' that of the faint, diffuse ionized gas observed in Lyα at similar radii from the central radio galaxy [13, 12]. Given the atypical properties of this CO line emitter, and proximity with the radio jet (spatially) and diffuse gas (spectrally), we suspect we may have detected a cloud or filament of cold gas, that is excited or may even be compressed by weak shocks from the radio source.

Hydrodynamic jet models suggest that cloud collapse (and perhaps star formation) may actually be enhanced through shocks driven by the expanding radio source ('jet-induced star formation' or 'positive feedback') [39, 40]. Extended filaments of cold molecular gas have been observed in nearby X-ray luminous clusters where they seem to be a by-product of interactions between the radio jet and the cluster gas, which will ultimately heat the diffuse cluster gas. More observations of similar stuctures will be necessary to confirm this rough scenario of jet-induced gas collapse at high redshift, which is based on deep observations with IRAM after a recent, major upgrade, and a non-standard target selection. With the advent of ALMA we will be able to further explore the many roles of molecular gas in forming stars and shaping galaxies in the early Universe.

NPHN acknowledges financial support through a fellowship of the Centre Nationale d'Etudes Spatiales (CNES).

References

Benson, et al. 2003, ApJ, 599, 38
Croton, D. J., et al. 2006, MNRAS, 365, 11
Silk, J., & Rees, M. J. 1998, A&A 331, L1
Antonuccio-Delogu, V., & Silk, J. 2008, MNRAS, 389, 1750
McNamara, B. R., & Nulsen, P. E. J. 2007,ARAA, 45, 117
Best, P. N., et al. 2006, MNRAS, 368, L67
Holt, J., Tadhunter, C. N., & Morganti, R. 2008, MNRAS, 387, 639
De Breuck, et al. 2002, AJ, 123, 637
Seymour, N., et al. 2007, ApJ, 171, 353
Reuland, M., et al. 2004, MNRAS, 353, 377
Archibald, E. N., et al. 2001, MNRAS, 323, 417
Villar-Martín M., et al. 2003, MNRAS, 346, 273
Villar-Martín M., et al. 2002, MNRAS, 336, 436
Villar-Martín M., et al., 2007, MNRAS, 378, 416
Villar-Martín M., et al., 2006, MNRAS, 366, L1
Humphrey, A., et al. 2008, MNRAS, 383, 11
Nesvadba N. P. H., et al. 2006, ApJ, 650, 693
Nesvadba N. P. H., et al. 2007, A&A, 475, 145
Nesvadba N. P. H., et al. 2008, A&A, 491, 407
Humphrey, A., et al. 2008, MNRAS, 390,1501
Hatch, N. A., et al. 2009, MRAS, 395, 114
Law, D. R., et al 2007, ApJ, 669, 929
Wright, S. A., et al.. 2008, arXiv:0810.5599
van Starkenburg, L., et al. 2008, A&A, 488, 99
Nesvadba N. P. H., et al. A&A, 479, 67
Bournaud F., et al., 2008, A&A, 486, 741
Law, D. R., et al. 2009, ApJ, 697, 2057
Forster Schreiber N. M., et al., 2009,arXiv:0903.1872
Epinat, B., et al. 2009, arXiv:0903.1216
Le Fevre, O., et al. 1996, ApJL, 471, L11
Miley, G. K., et al. 2006,ApJL, 650, L29
Venemans, B. P., et al. 2007, A&A, 461, 823
Lehnert M. D., et al. 2009,arXiv:0902.2784
Nesvadba N. P. H., et al., 2007, ApJ, 657, 725
Nesvadba N. P. H., et al., 2009, MNRAS, 395, L16

Nath, B. B., & Roychowdhury, S. 2002,MNRAS, 333, 145
McCarthy, I. G., et al. 2008,MNRAS, 386, 1309
Villar-Martín M., Sánchez S. F., Humphrey A., Dijkstra M., di Serego Alighieri S., De Breuck C., González Delgado R., 2007, MNRAS, 378, 416
Mellema, G., Kurk, J. D., & Röttgering, H. J. A. 2002, A&A, 395, L13
Fragile, P. C., Murray, S. D., Anninos, P., & van Breugel, W. 2004, ApJ, 604, 74